Analysis of Thermal Paths in 3-D Structures

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Two important issues in modern ICs are heterogeneity and global signaling. Coupling between different circuits has increased with greater on-chip integration. A natural solution is to use a 3-D structure, where each layer is fabricated separately, and all of the layers are stacked to form a heterogeneous system. However, as the vertical dimension becomes blocked by additional stacked layers, the heat is not as easily transferred towards the heat sink as in 2-D circuits. With higher temperature, the mobility of the charge carriers decreases, which consequently slows the circuit. An important issue is therefore identifying thermal paths within a 3-D integrated system.

The thermal resistance per unit length is a useful metric to characterize the thermal behavior of the horizontal and vertical paths. Results from a 3-D structure, modeled using the HotSpot simulator, as well as experimental results from a fabricated test vehicle, are shown in Figure 1. The thermal resistance per unit length of the vertical path is two orders of magnitude larger than the thermal resistance of the horizontal path, since SiO_2 exhibits two to three orders of magnitude lower thermal conductivity than silicon. The dependence of the thermal conductivity on temperature is also analyzed in this work. A comparison among the constant thermal conductivity, temperature dependent thermal conductivity, and experimental results is shown in Figure 1 for two paths. The results based on a constant thermal conductivity deviate from experimental measurements by up to 25% and 36% for, respectively, the vertical and horizontal paths, while the results based on a temperature dependent thermal conductivity only deviate by 13% and 12% for the same paths.

Heat propagation in the vertical dimension is shown to be poor; the heat primarily passes along the horizontal dimension. Vertical heat removal paths are therefore needed to reduce degradations in performance caused by thermal gradients. This analysis confirms the importance of accurately modeling the thermal conductivity, and integrating accurate thermal conductivity models into the thermal analysis process.

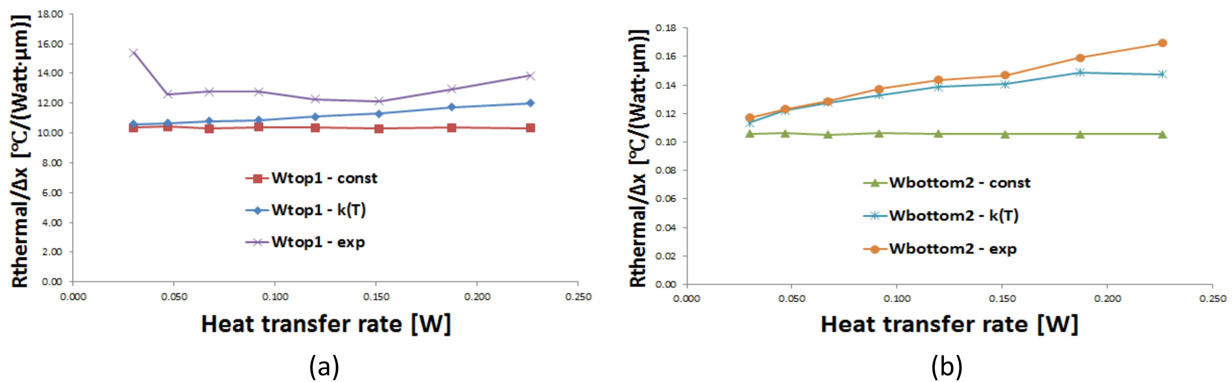

Figure 1: Thermal resistance per unit length of (a) a vertical path, and (b) a horizontal path within the 3-D structure.